

A search for charged lepton flavor violation in muon to electron conversion



Mu2e collaboration: \sim 140 physicists



Boston University
Brookhaven National
Laboratory
LBL/UC Berkeley
University of California,
Irvine
California Institute of
Technology
City University of New York
Duke University
Fermi National Accelerator
Laboratory
University of Houston

University of Illinois
Lewis University
University of
Massachusetts,
Amherst
Muons, Inc.
Northern Illinois
University
Northwestern
University
Pacific Northwest
National Laboratory
Rice University
University of Virginia
University of
Washington



INFN Lecce/Università del Salento
INFN Lecce/Università Marconi
INFN Pisa
Universita di Udine/INFN
Trieste/Udine
Laboratori Nazionali di Frascati



Institute for Nuclear Research,
Moscow
Joint Institute for Nuclear Research,
Dubna

Opportunities for new people to join!

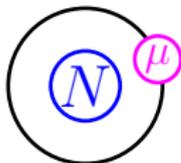
Outline

- Introduction to charged lepton flavor violation (CLVF)
(Focus on searches with muons — there are also τ , Z , ...)
- Experimental considerations
- Mu2e at Fermilab (CDR: [arXiv:1211.7019](#))
 - Design of the experiment
 - Expected performance
- Conclusion

Introduction

Mu2e searches for

Coherent muon to electron
conversion on nucleus



- Initial state is a bound muon
- Nucleus participates in the process
- But remains intact in the end

Introduction

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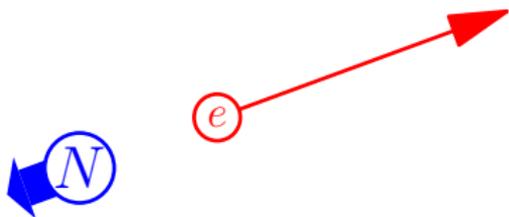
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Introduction

Mu2e searches for

Coherent muon to electron
conversion on nucleus

$$\mu^- N \rightarrow e^- N$$



Compare to

Normal muon decay:

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$



Flavor violating decay

$$\mu^- \rightarrow e^- \gamma$$

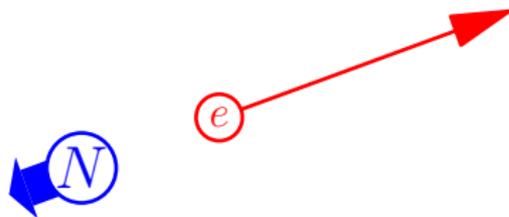


Introduction

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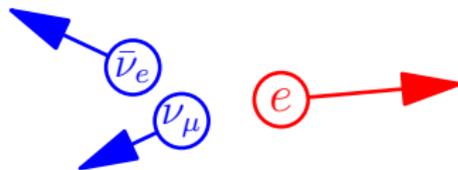
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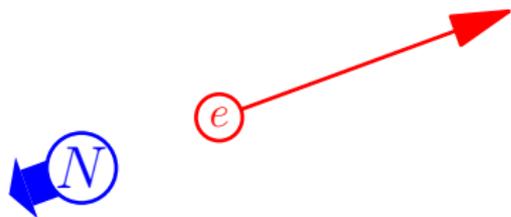


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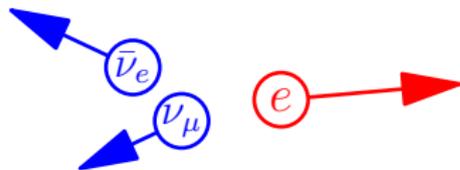
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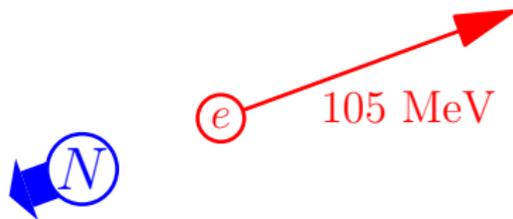


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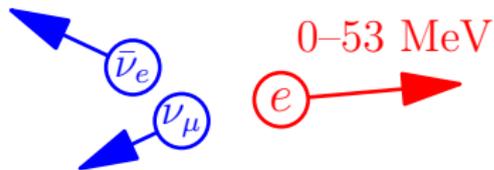
$$\mu^- N \rightarrow e^- N$$



Compare to

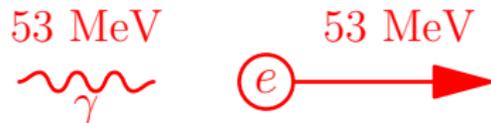
Normal muon decay:

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$



Flavor violating decay

$$\mu^- \rightarrow e^- \gamma$$

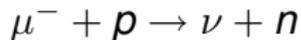


The number we measure

- **Signal:** coherent muon to electron conversion on nucleus
- **Normalization:** all nuclear captures
 - reduces theory uncertainty (nuclear wavefunction cancels)

$$R_{\mu e} = \frac{\Gamma[\mu^- + (A, Z) \rightarrow e^- + (A, Z)]}{\Gamma[\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z - 1)^*]}$$

Simplest capture example:

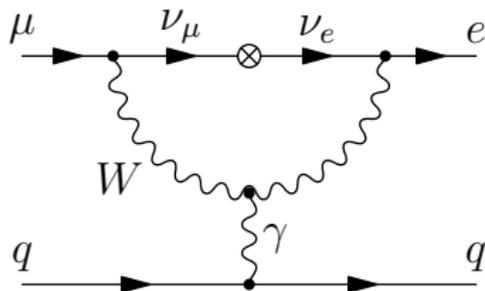


Charged lepton flavor violation

- Neutral lepton flavor violation has been observed

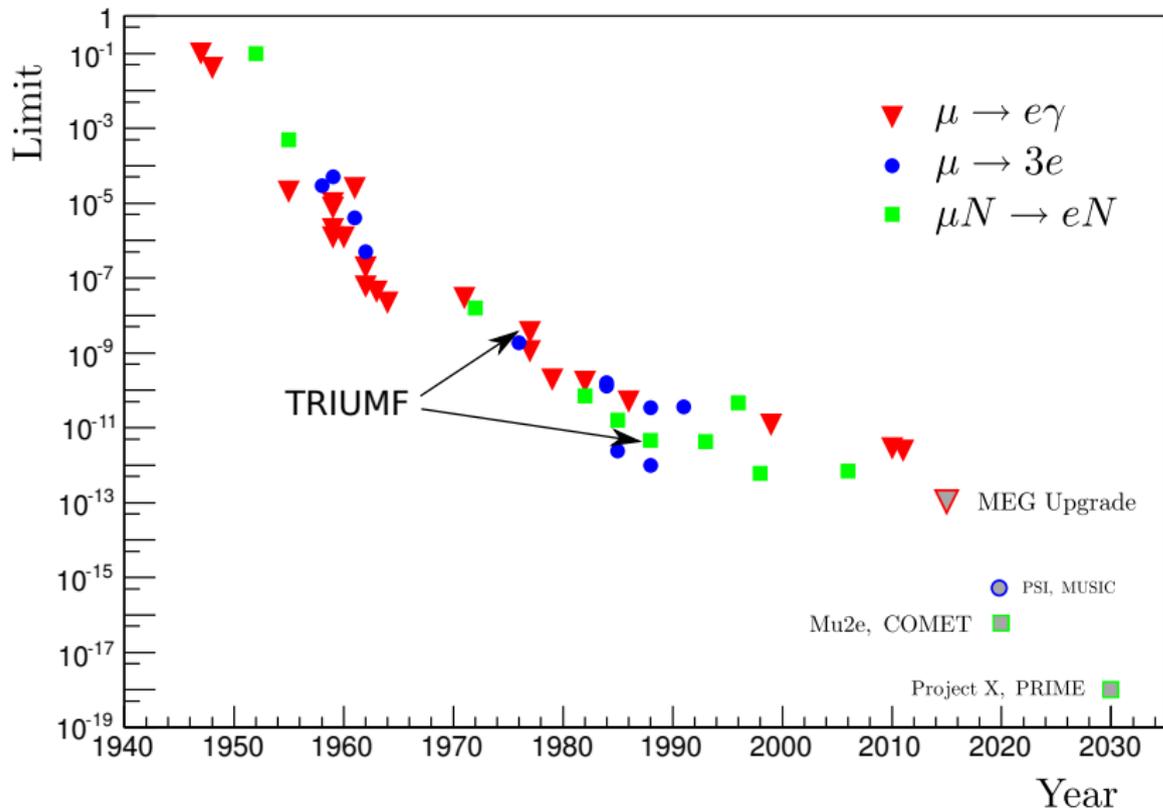


- Induces CLFV



- Induced rate: about 40 orders of magnitude below experimental limits
- CLFV observation would still be an unambiguous proof of New Physics

CLFV history



R. H. Bernstein, P. S. Cooper
Physics Reports [in preparation]

CLFV history

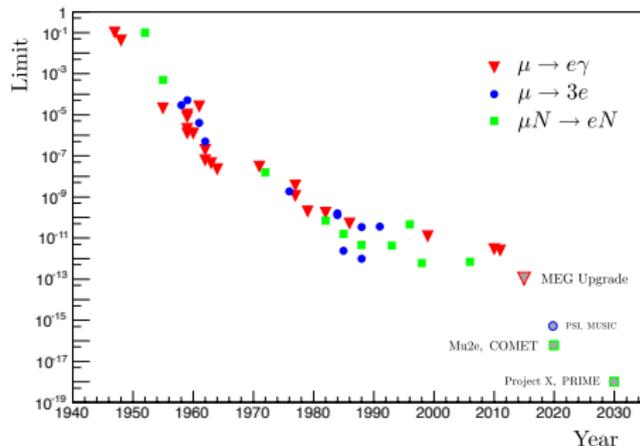
Concept of generations

- Muon is not an excited electron
- $\mu \rightarrow e\gamma$ limits: two neutrino hypothesis

Constraints on models of new physics

Today's best limits

- $R_{\mu e} < 7 \times 10^{-13}$ SINDRUM-II 2006
 $Br(\mu \rightarrow e\gamma) < 2.4 \times 10^{-12}$ MEG 2011
 $Br(\mu \rightarrow 3e) < 1 \times 10^{-12}$ SINDRUM-I 1988



Mu2e goal

Single event sensitivity

$$R_{\mu e} = \text{few} \times 10^{-17}$$

CLFV history

Concept of generations

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- $\mu \rightarrow e\gamma$ limits: two neutrino hypothesis

Constraints on models of new physics

Today's best limits

$$R_{\mu e} < 7 \times 10^{-13}$$

$$Br(\mu \rightarrow e\gamma) < 2.4 \times 10^{-9}$$

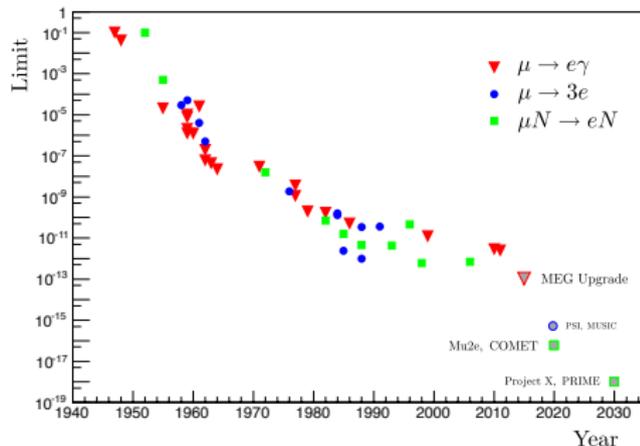
$$Br(\mu \rightarrow 3e) < 1 \times 10^{-9}$$

Mu2e goal

10⁻¹⁴ event sensitivity

$$1 \times 10^{-17}$$

Relevancy in the LHC era?

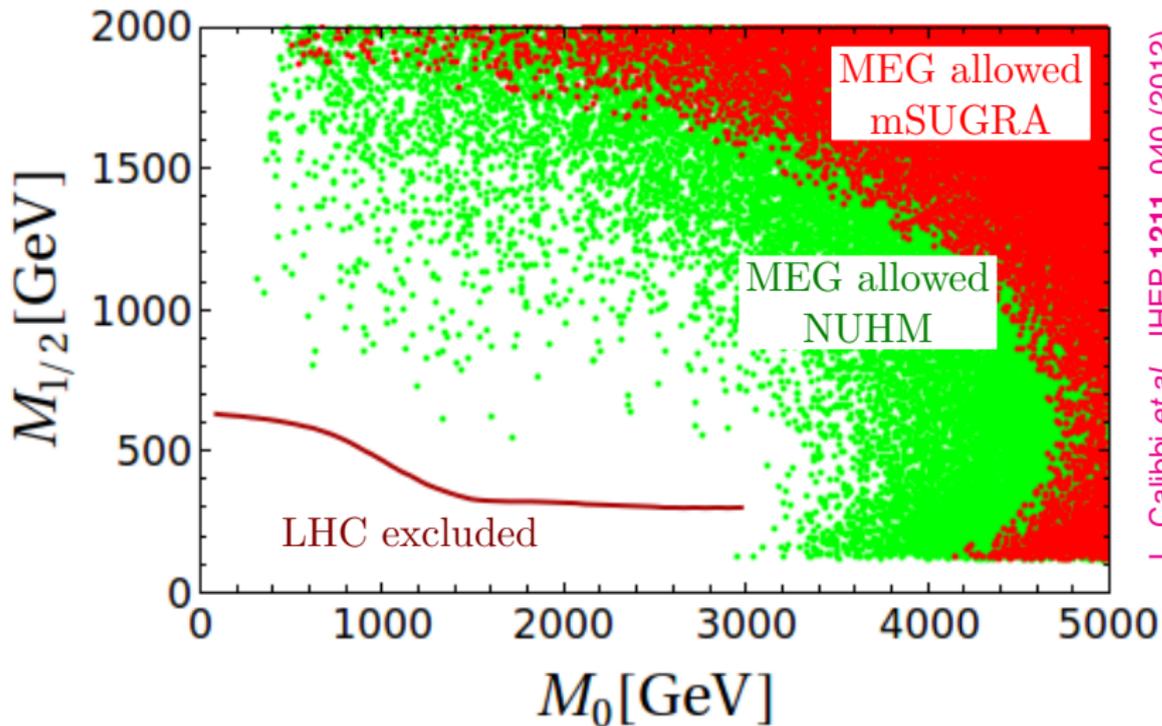


CLFV vs direct LHC searches

An example

- SUSY seesaw GUT models
- Recent analysis [L. Calibbi *et al.*, JHEP **1211**, 040 \(2012\)](#)
- Takes into account
 - LHC Higgs mass measurement
 - θ_{13} measurement
 - $Br(\mu \rightarrow e\gamma) < 2.4 \times 10^{-12}$ from [MEG \(2011\)](#)
- Compares direct LHC-2012 limits with flavor constraints

CLFV vs direct LHC searches



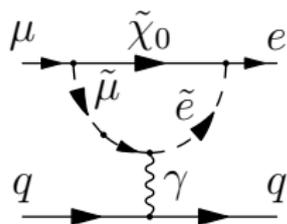
L. Calibbi *et al.*, JHEP 1211, 040 (2012)

Complementarity with the LHC

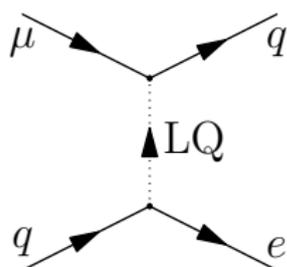
- Today's best constraints
 - Direct searches for some cases
 - CLFV for others
- If new physics is seen at LHC
 - Need CLFV measurements to discriminate models
- If no LHC signal
 - Mu2e can still make a discovery

Many New Physics models

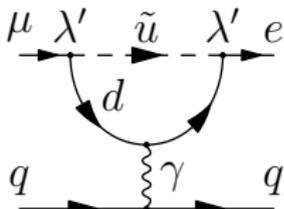
SUSY



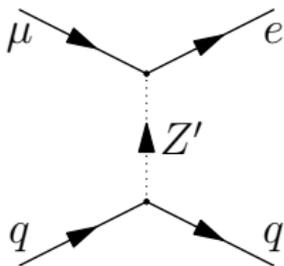
Leptoquarks



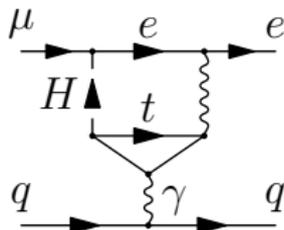
RPV SUSY



Z' /anomalous couplings



Second Higgs doublet



Extra dimensions, etc.

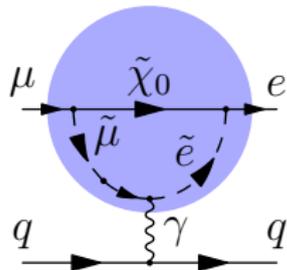
Some reviews:

Kuno, Okada, 2001

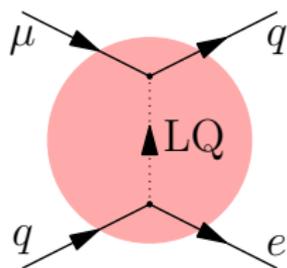
M. Raidal *et al.*, 2008

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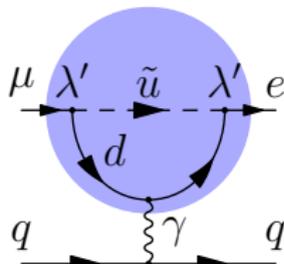
SUSY



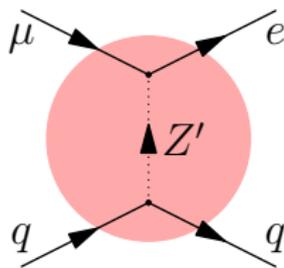
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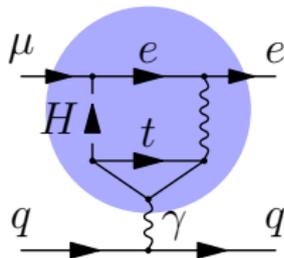
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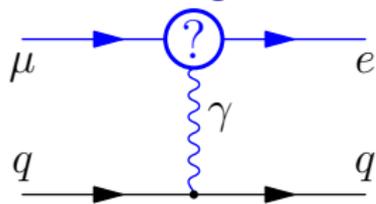
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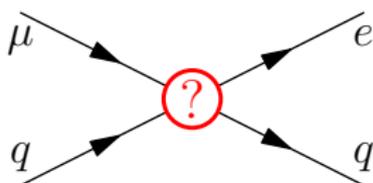
Effective theory

Electromagnetic vertex



Often gives large $Br(\mu \rightarrow e\gamma)$

Contact interaction:



May be no $\mu \rightarrow e\gamma$ signal

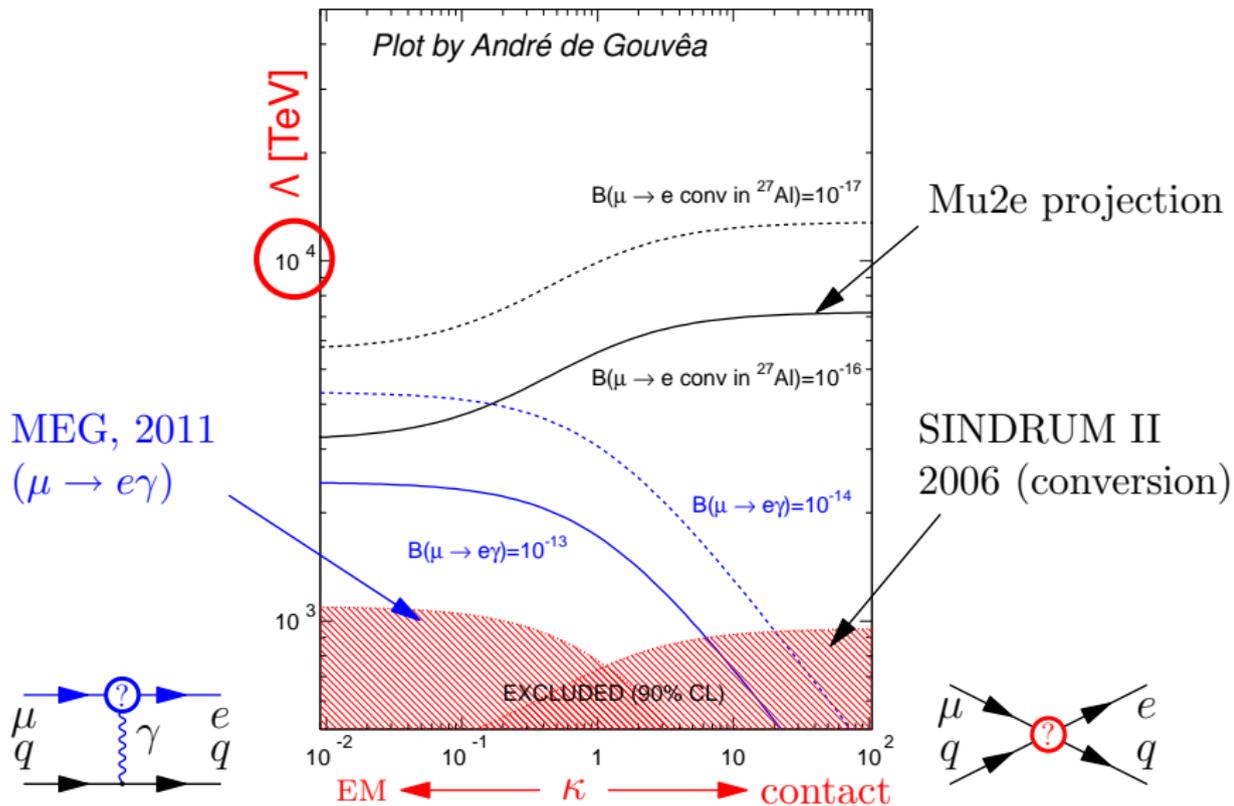
Relative rates of conversion and $\mu \rightarrow e\gamma$ are model dependent
Handle to discriminate New Physics models

Parametrization: $\mathcal{L}_{CLFV} =$

$$\frac{m_\mu}{(1 + \kappa)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1 + \kappa)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L)$$

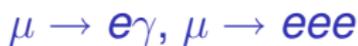
Λ : mass scale, κ : importance of contact term

Muon LVF physics reach



Experimental considerations

Decays vs conversion



- Signal particles < 53 MeV
 - high background region
- Signal: **combination** of particles
 - Background rejection: cuts on the **combination**
 - **Accidental coincidences** limit usable muon rate
 - MEG: $3 \times 10^7 \mu/s$
- Reduce instantaneous rate: **continuous beam**



- Signal particle **at 105 MeV**
 - Away from Michel peak
- Signal: **single track**
 - **Fewer handles to reject background**
 - Coincidences not a problem
 - Mu2e: $\approx 10^{10} \mu/s$
- Use **pulsed beam**: less background between pulses
- Need **cosmic ray veto**

μ^+ VS μ^-

- Stopped muons
 - Decay rates: $\Gamma_{\mu^+} = \Gamma_{\mu^-}$
 - Stopping target contains protons but not \bar{p}
 - Capture rates: $\Gamma_{\mu^+} = 0$, $\Gamma_{\mu^-} \propto Z^4$ [review by Measday]
- Vacuum: $\tau_{\mu^-} = \tau_{\mu^+} = 2197$ ns
Al: $\tau_{\mu^-} = 864$ ns, Au: $\tau_{\mu^-} = 72.6$ ns
- Capture process: ejects n , p , γ , ...
 - Potential backgrounds
- Surface muon beams: μ^+ but not μ^- (pion capture)
- Proton beam: makes more μ^+ than μ^-

All in all: decay experiments use μ^+ , conversion μ^-

The concept of Mu2e measurement

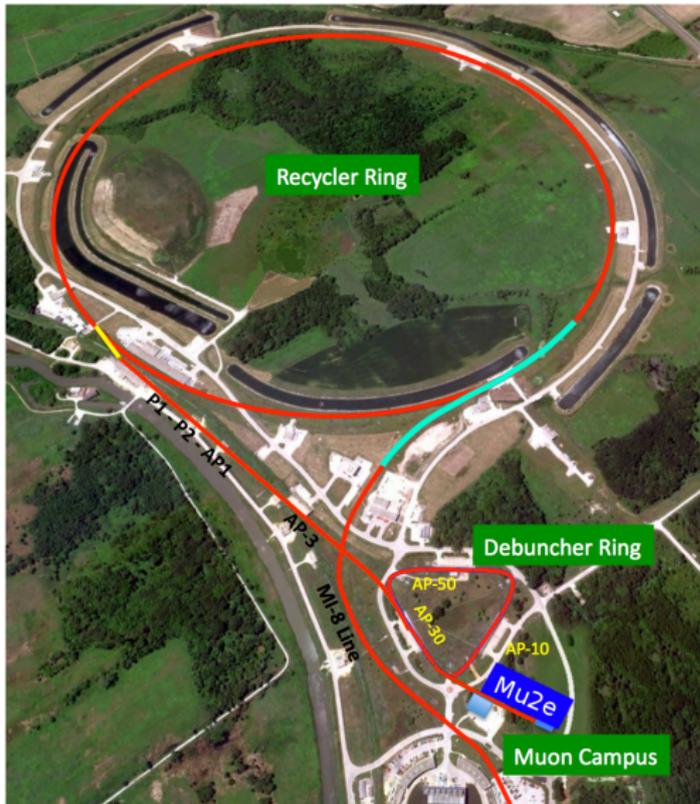
- Generate pulsed beam of low momentum negative muons
- Stop muons in thin foils and form muonic atoms
 - μ^- in aluminum: $\tau^{\text{Al}} = 864$ ns
- Wait for prompt backgrounds to decay
- Then measure electron spectrum
 - The signal: mono-energetic electrons at 105 MeV

Types of backgrounds

- Muon induced
 - Muon decay in orbit (DIO)
- Protons arriving out of time
 - Radiative pion capture
 - Muon decay in flight
 - Pion decay in flight
 - Beam electrons
- Long transit through muon beamline
 - *Antiprotons*
- Cosmic rays

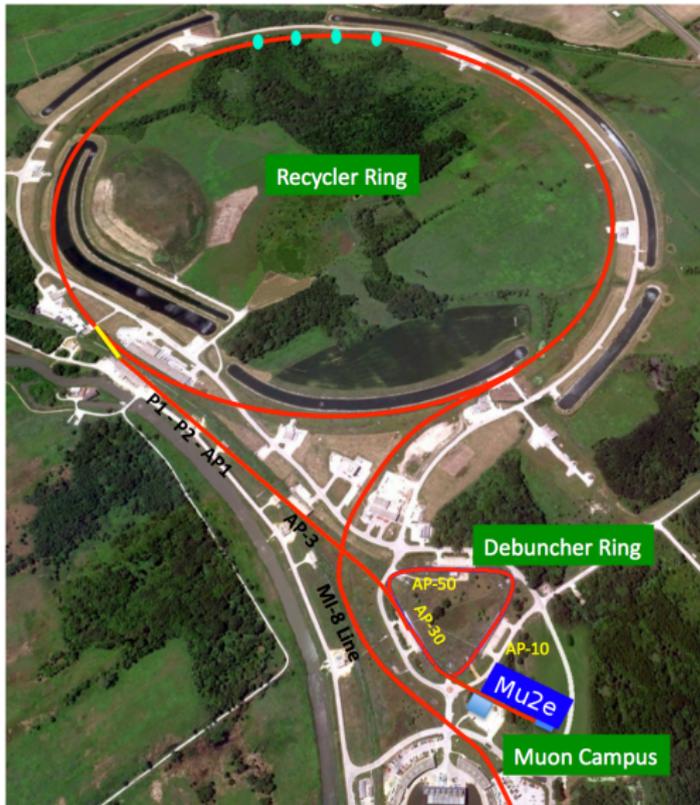
Mu2e at Fermilab

Proton delivery



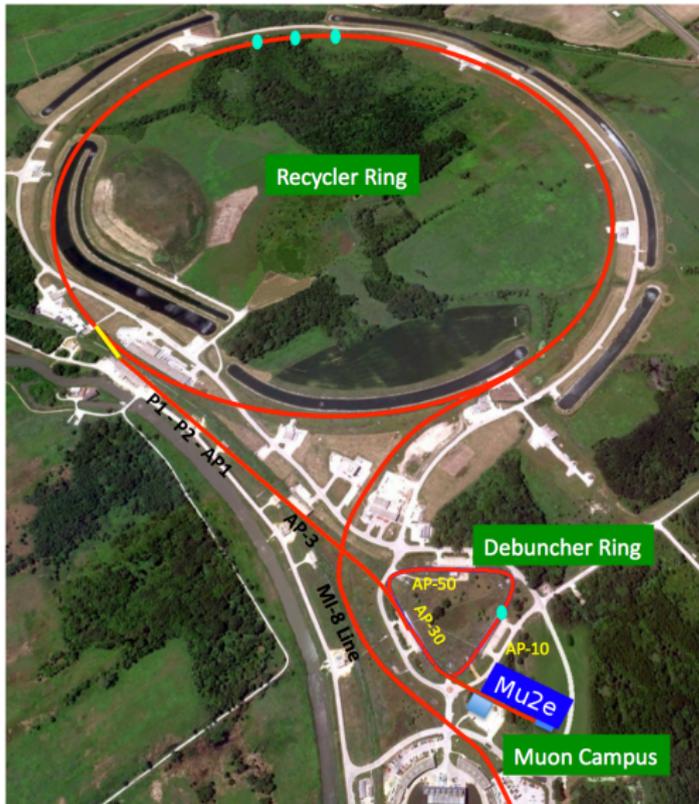
- Efficient reuse of Tevatron infrastructure
- Muon campus: former antiproton complex
 - g-2 and Mu2e
- A muon experiment can run simultaneously with NOvA
- Ring revolution period is 1694 ns: good match to $\tau^{Al} = 864$ ns

Proton delivery



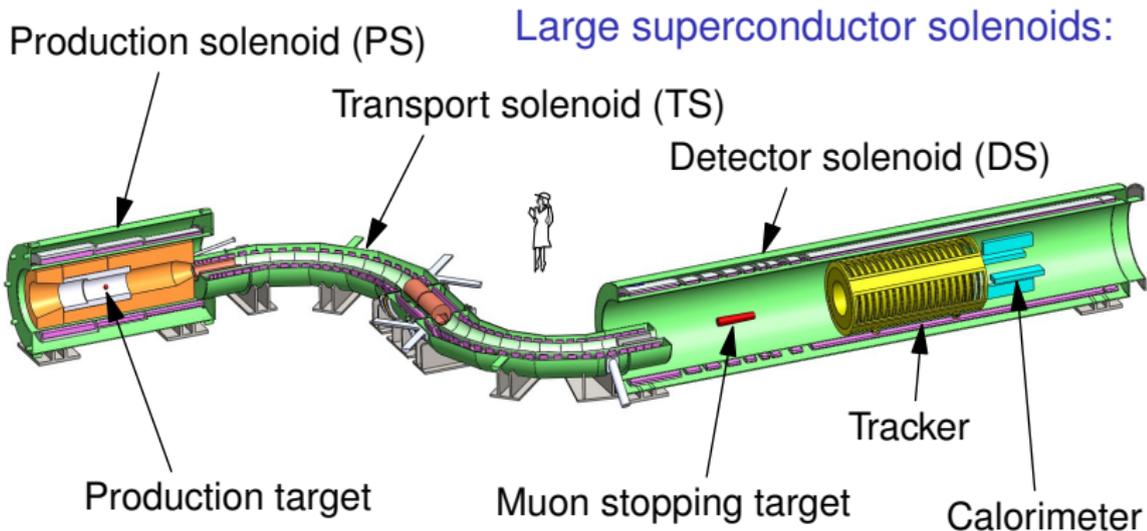
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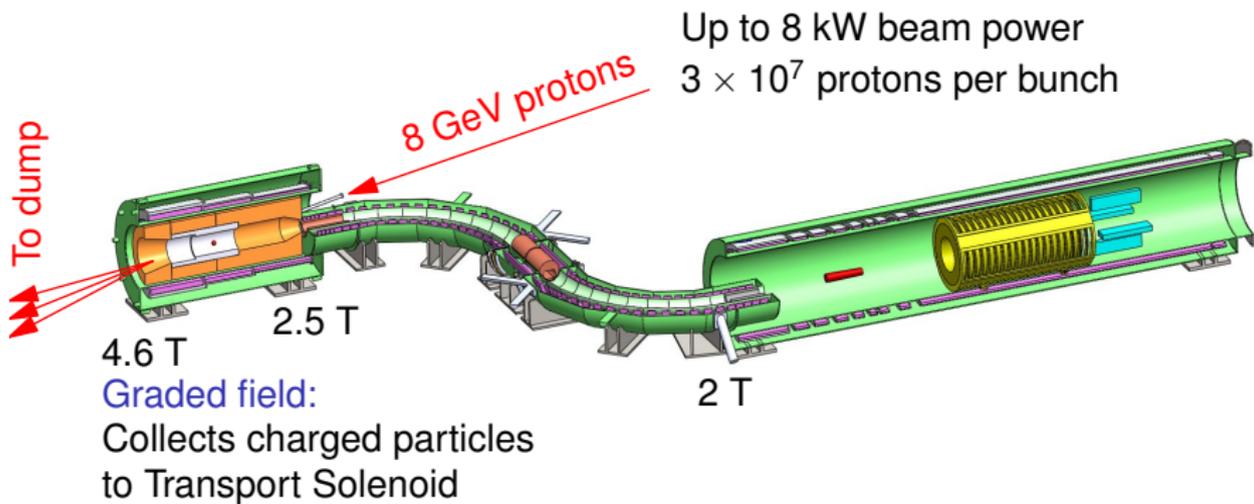
Mu2e experiment



Not shown:

Cosmic ray veto, Extinction monitor, Stopping target monitor

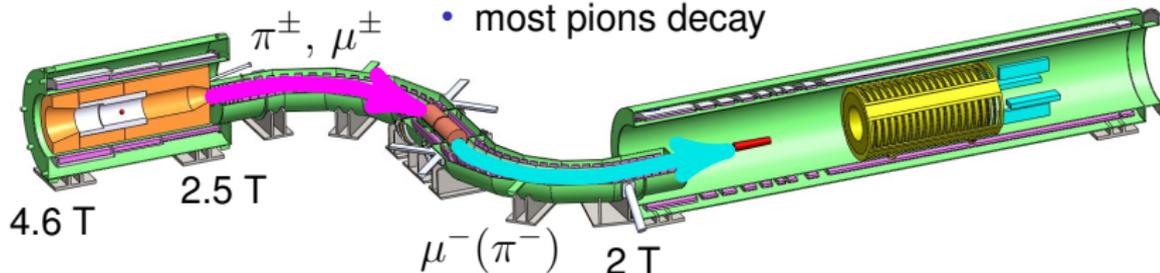
Mu2e experiment



Mu2e experiment

S-shaped solenoidal beamline
with asymmetric collimators:

- charge and momentum selection
- most pions decay

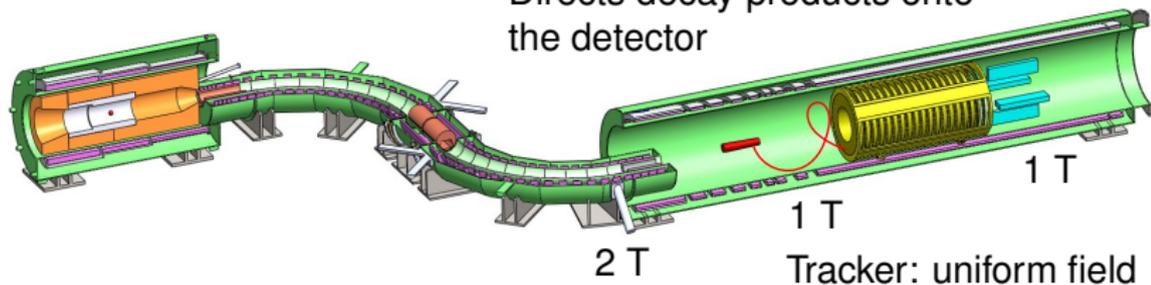


Muon stopping target

- thin aluminum disks
- Stops 40% muons
- **0.0016** stopped muons per proton

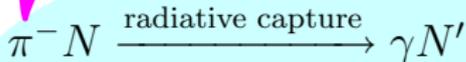
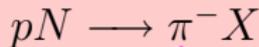
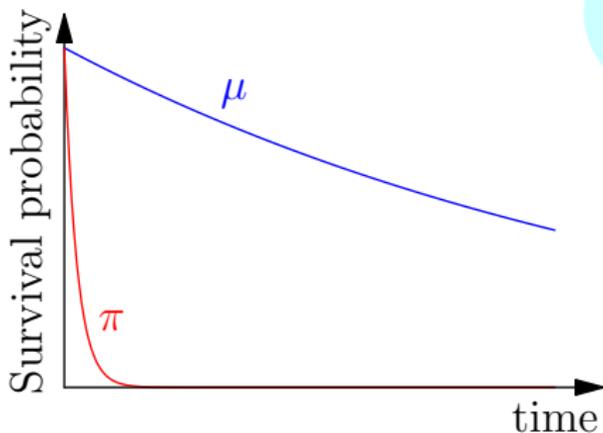
Mu2e experiment

Graded field at Al stopping target:
Directs decay products onto
the detector



Prompt backgrounds

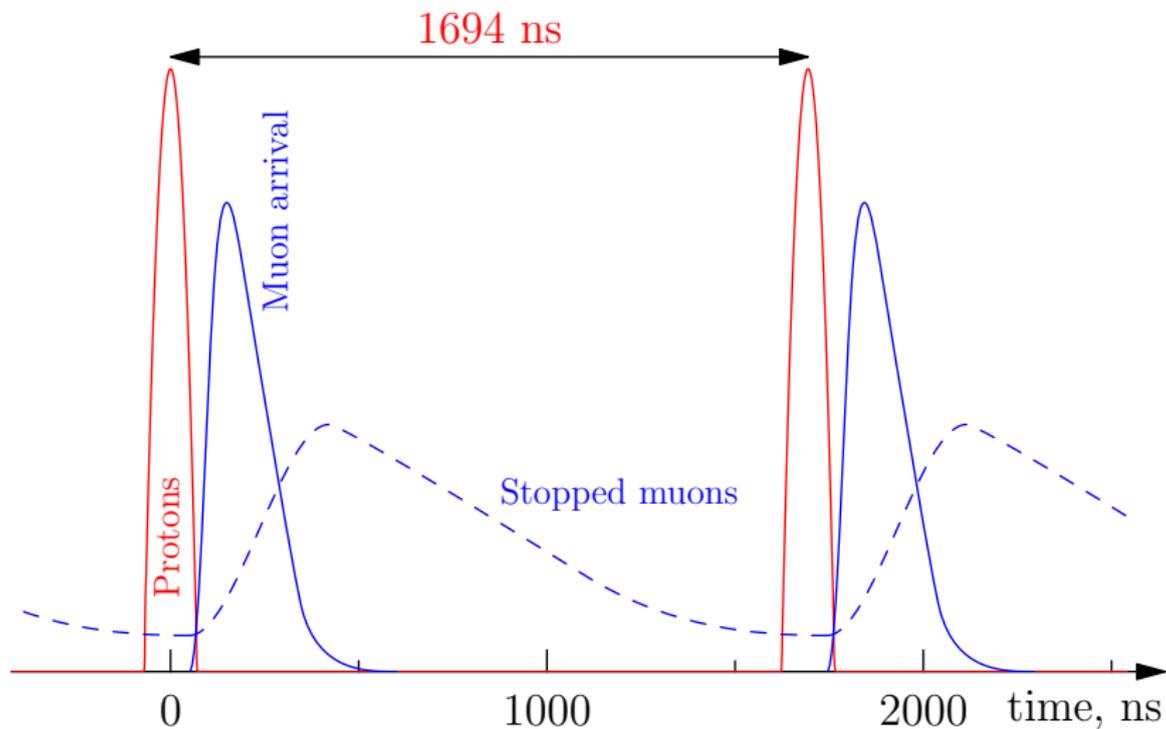
- Signal is a 105 MeV electron
- Many ways for 8 GeV protons to make those
- Example: Radiative Pion Capture



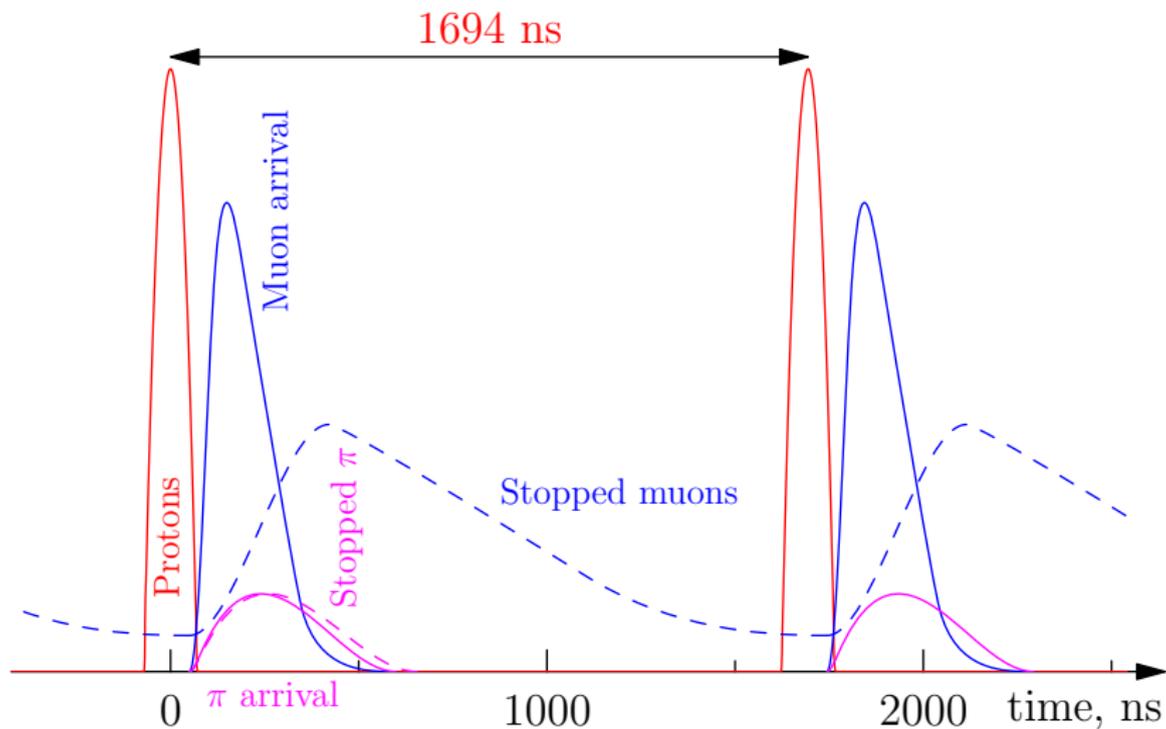
Processes in Al target

⇐ Mitigation: wait

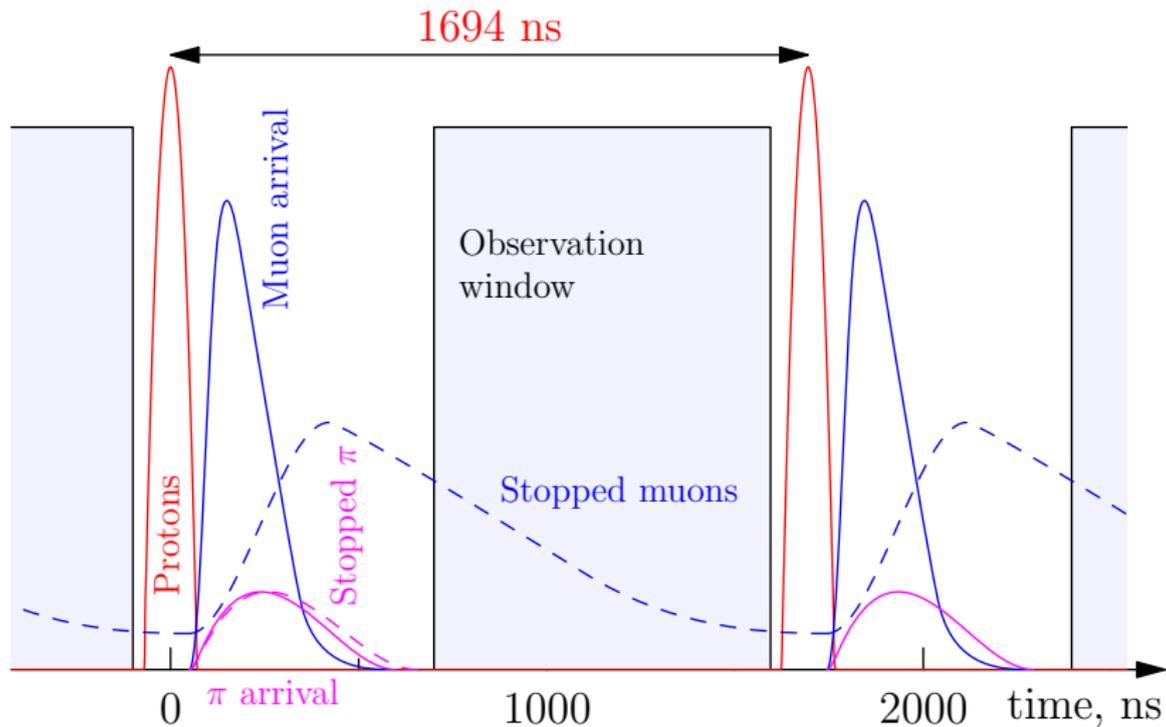
Time structure



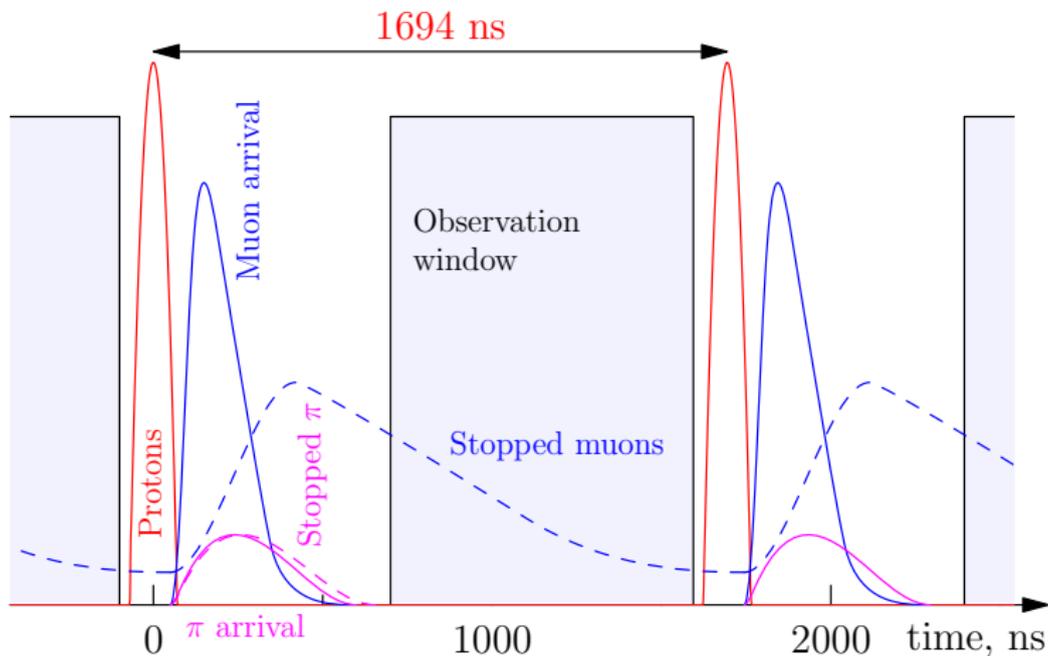
Time structure



Time structure



Proton beam extinction



Beam extinction requirement

$$\epsilon = (\text{Num protons between pulses}) / (\text{Num in pulses}) < 10^{-10}$$

Achieving $\epsilon = 10^{-10}$: two stages

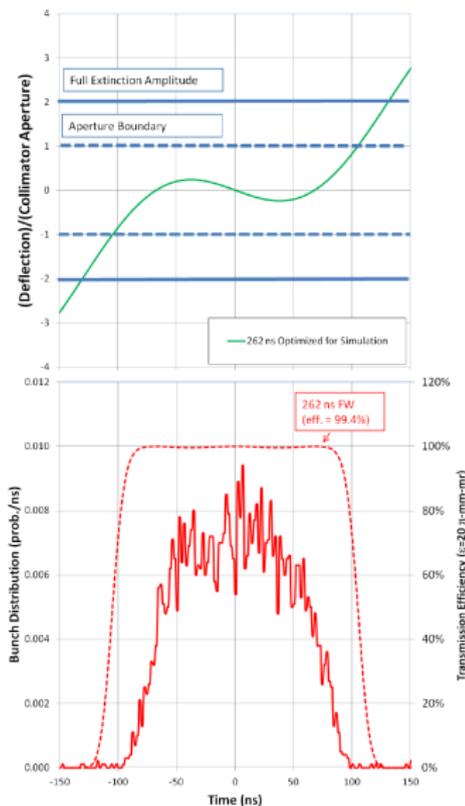
In delivery ring: better than 10^{-4}

- 1 bunch circulates at a time
- At injection $\epsilon \approx 10^{-5}$
- Degrades during slow extraction
 - RF noise, beam gas, ...

Extraction beamline: $\times 10^{-7}$

Deflect late beam with extinction magnets

- 600 kHz bunches: beyond state of art for kickers
- Use resonant dipoles 300 kHz and 3800 kHz



How to measure $\epsilon = 10^{-10}$

One could try

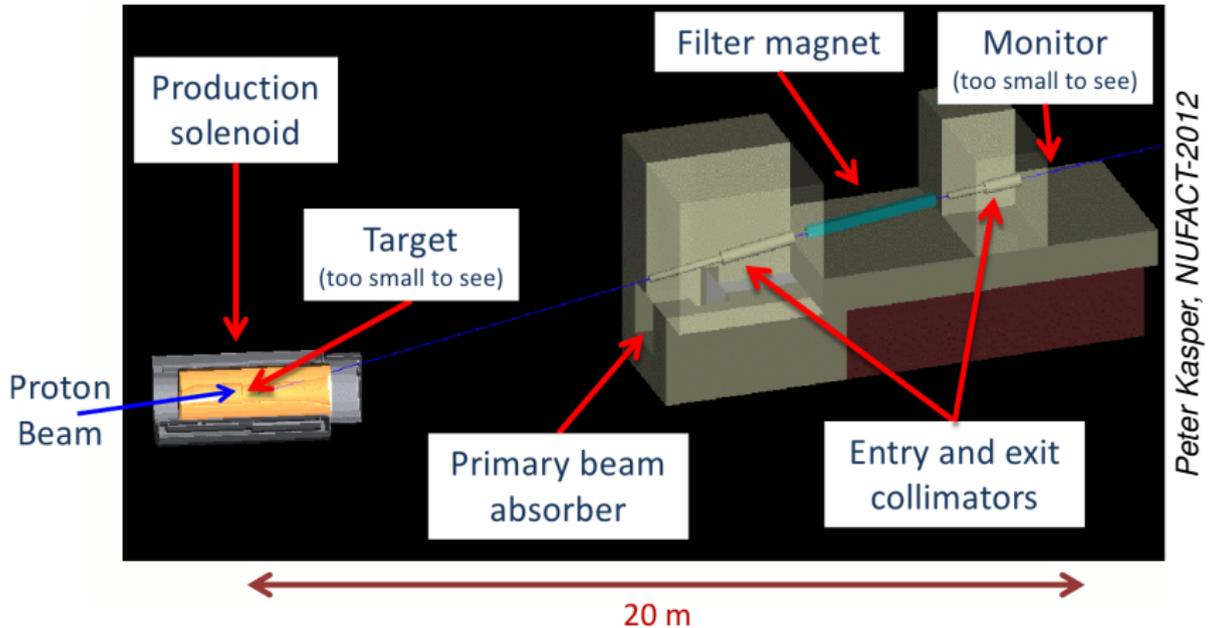
- Count 3×10^7 protons during ≈ 150 ns pulse
- Be sensitive to single proton for the rest of 1694 ns cycle
 - With background $\ll 10^{-3}$ counts/cycle

Mu2e approach: use statistical sampling instead

- Count $\mathcal{O}(30)$ secondary tracks/pulse
- Integrate over $\mathcal{O}(10^9)$ cycles ($\lesssim 1$ hour)
 - Get **3** out of time secondary tracks/integration at $\epsilon = 10^{-10}$
- Need $\ll 1/\text{integration} = 10^{-9}/\text{cycle}$ backgrounds
 - **While monitoring the high intensity proton beam!**

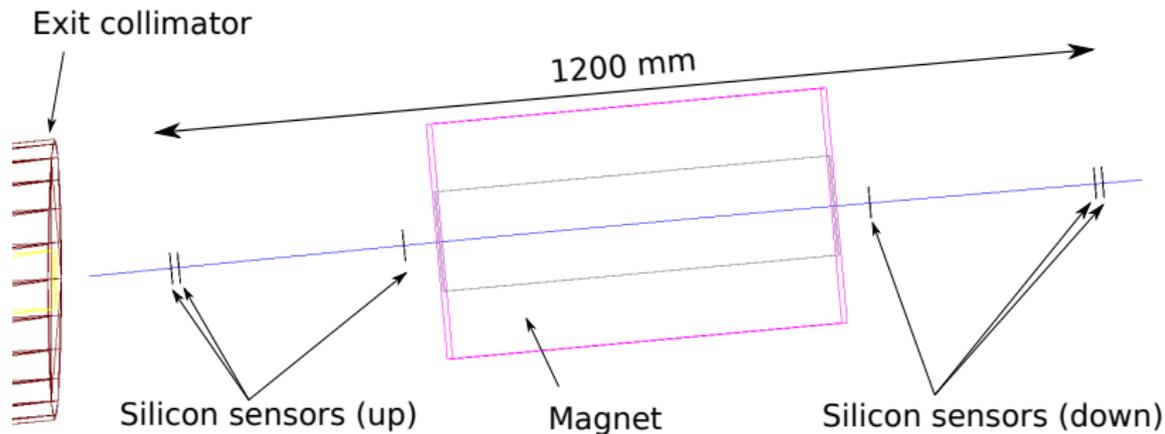
Extinction monitor

- Select positive tracks of a few GeV/c originating in the proton target with collimators and a permanent magnet



Extinction monitor

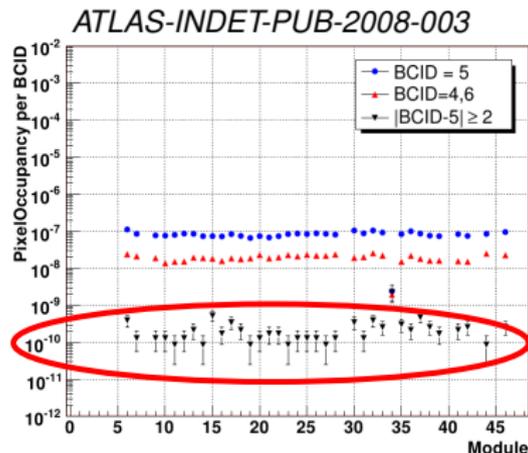
- Observe the tracks with a magnetic spectrometer



Candidate ExtMon detector technology

Silicon pixels

- demonstrated noise level
 10^{-10} hit/pixel/25 ns
- Radiation hard
- Fine granularity helps to fight backgrounds
- FE-I4 ATLAS IBL upgrade chip is a good match



Antiprotons are “special”

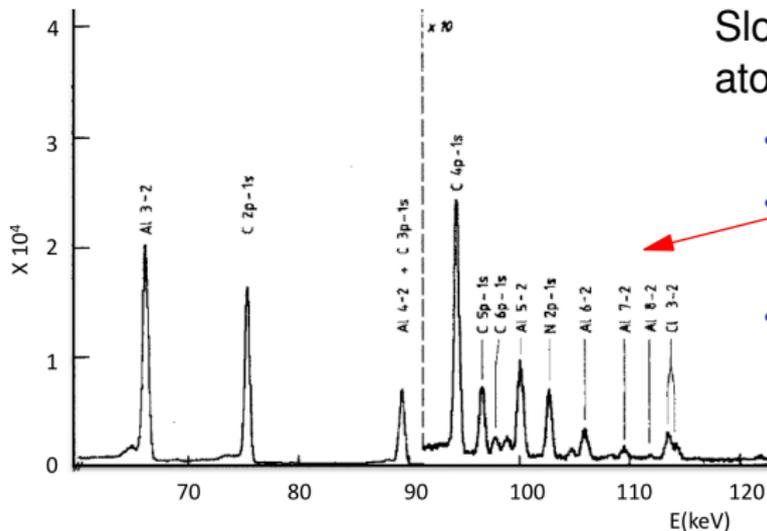
A source of background

- Negative—go through muon beamline
- Do not decay
- Heavy \implies slow
 - Arrive during signal window **even for perfect beam extinction**
 - **2 GeV shower**

Mitigation

- Thin window in the central collimator
- Reduces muon yield
- But effectively annihilates \bar{p}

Muons stopping in Al target



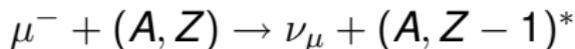
Slow down, form muonic atoms, cascade to 1s state

- picoseconds time scale
- **X-rays: use to count stopped muons**
- **Derive number of captures for normalization**

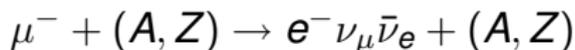
$$R_{\mu e} = \frac{\Gamma[\mu^- + (A, Z) \rightarrow e^- + (A, Z)]}{\Gamma[\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z - 1)^*]}$$

Muonic aluminum atom

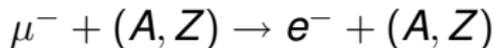
- $\approx 60\%$ Capture:



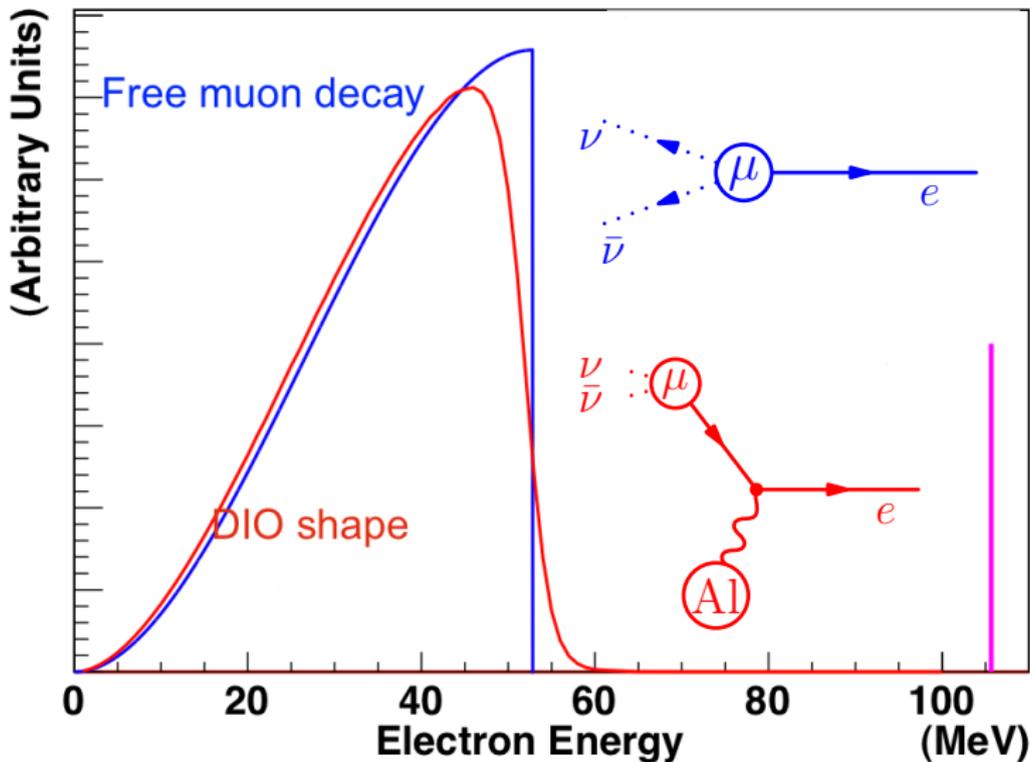
- $\approx 40\%$ Decay in orbit (DIO):



- Intrinsic background—scales with number of muons
 - Drives momentum resolution requirements
-
- New Physics: conversion?



Electron spectra



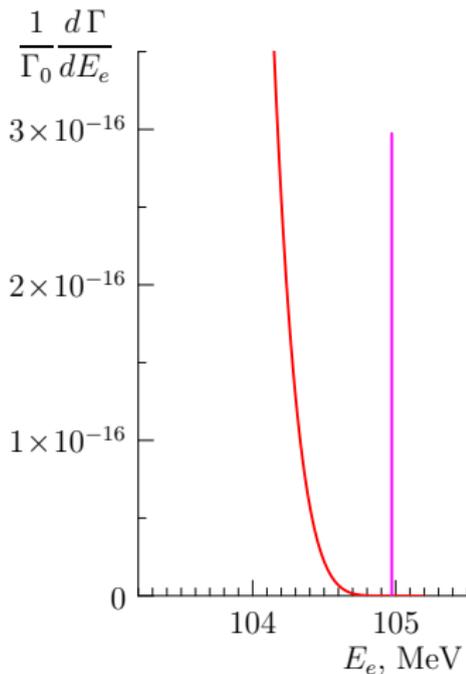
Decays in orbit

- Latest spectrum computation:
Czarnecki, Tormo, Marciano (2011)
- End point expansion

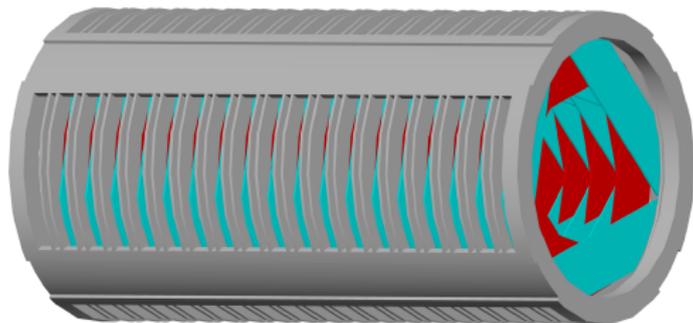
$$\frac{1}{\Gamma_0} \frac{d\Gamma}{dE_e} = B \left(E_\mu - E_e - \frac{E_e^2}{2m_N} \right)^5$$

— **small but steep tail!**

- DIO electron differs from signal only by its p
- **Momentum resolution is important!**
 - Especially the high side tail:
pushes DIOs into the signal region



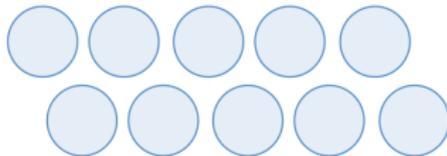
Tracker



- about 3 m long
- 1 T uniform B field
- “Good” tracks make 2–3 turns
- TDC readout on both ends
⇒ along-wire position from Δt
- ADC readout for particle ID

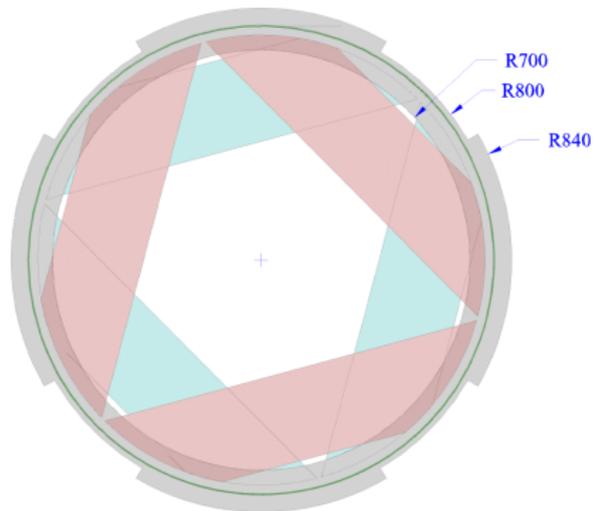
21,600 straw tubes

- 5 mm diameter
- 15 μm wall
- 25 μm wire
- in vacuum

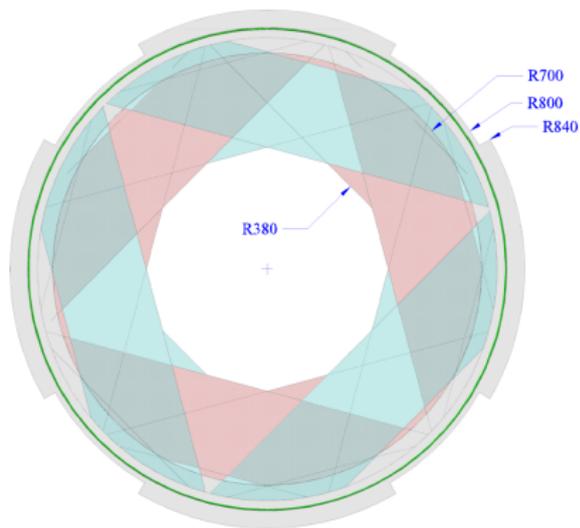


Tracker

Plane: Two layers



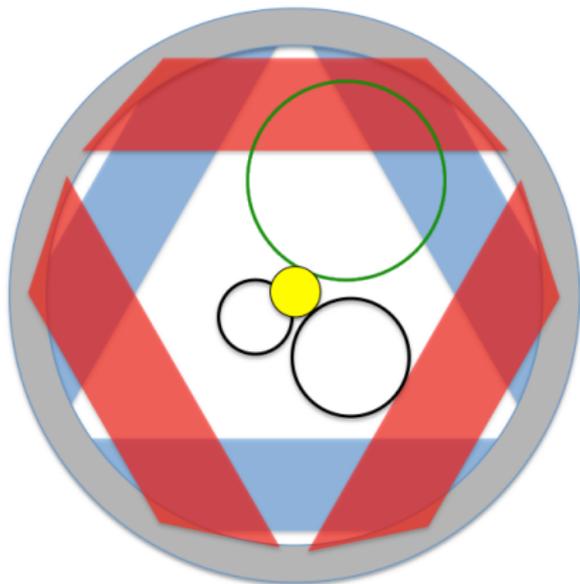
Station: Two planes



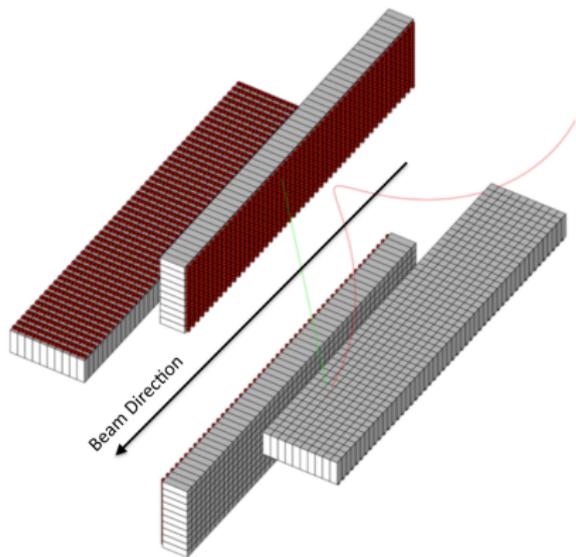
Tracker

No material in the middle

- Only tracks with $p_t > 53 \text{ MeV}/c$ can make hits
- DIOs from the peak **do not touch the tracker**

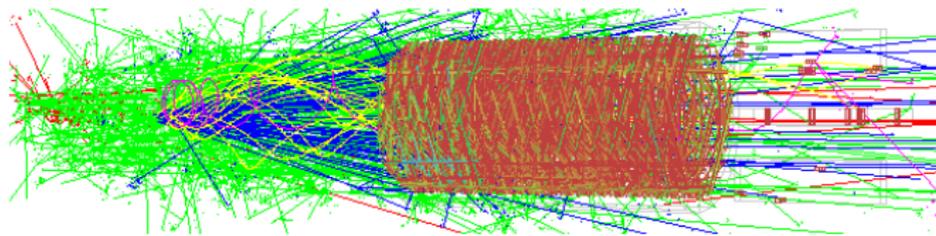


Calorimeter



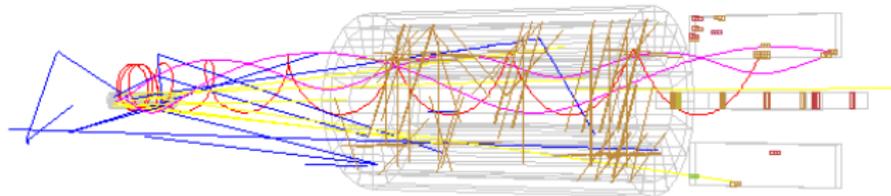
- 4 vanes of LYSO crystals
- Independent energy and position measurement
- Particle ID
- Independent trigger

Pattern recognition



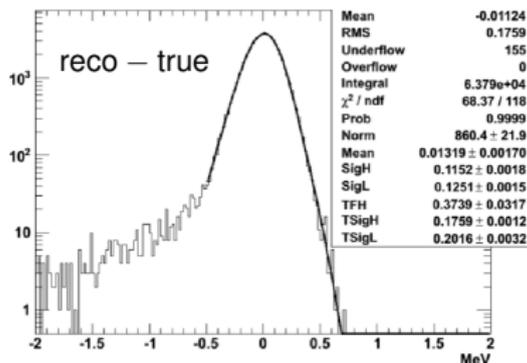
Single proton pulse: particles and hits in 500–1694 ns

Pattern recognition



Single proton pulse: particles and hits in ± 50 ns around conversion

Tracker performance (CDR)

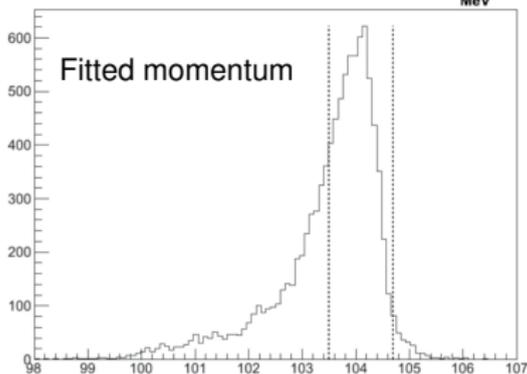


Intrinsic tracker resolution

High side:

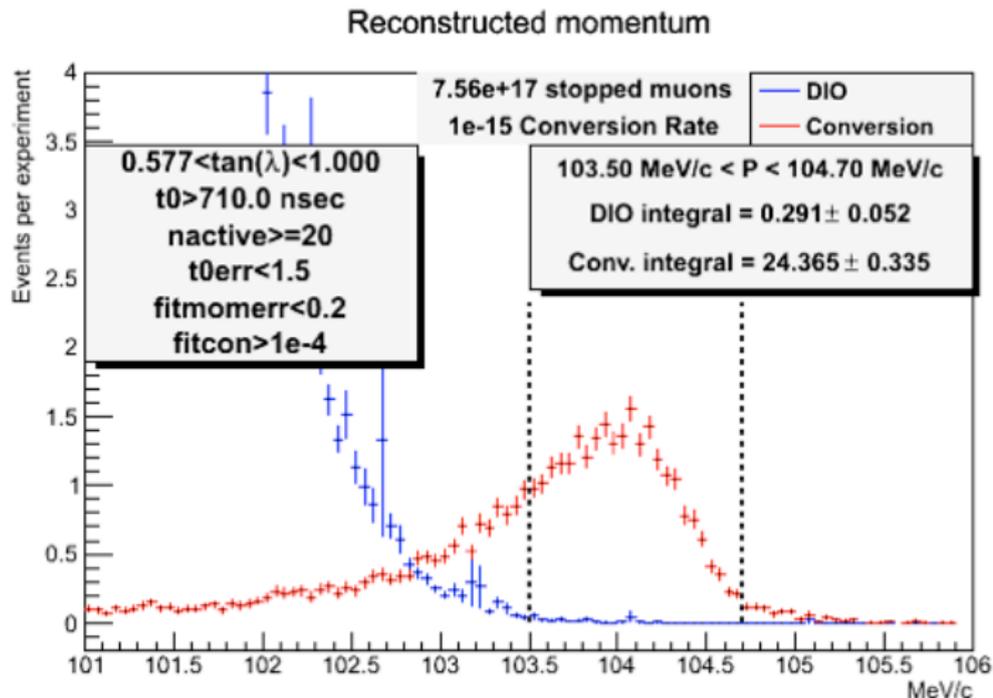
- Core: $\sigma \approx 115 \text{ keV/c}$
- Tail: $\sigma \approx 176 \text{ keV/c}$

Full G4 signal peak simulation



- FWHM $\approx 1 \text{ MeV/c}$
- Dominated by straggling before tracker
- Half of the straggling is in conversion Al

Reconstructed signal and backgrounds (CDR)



Backgrounds and sensitivity (CDR)

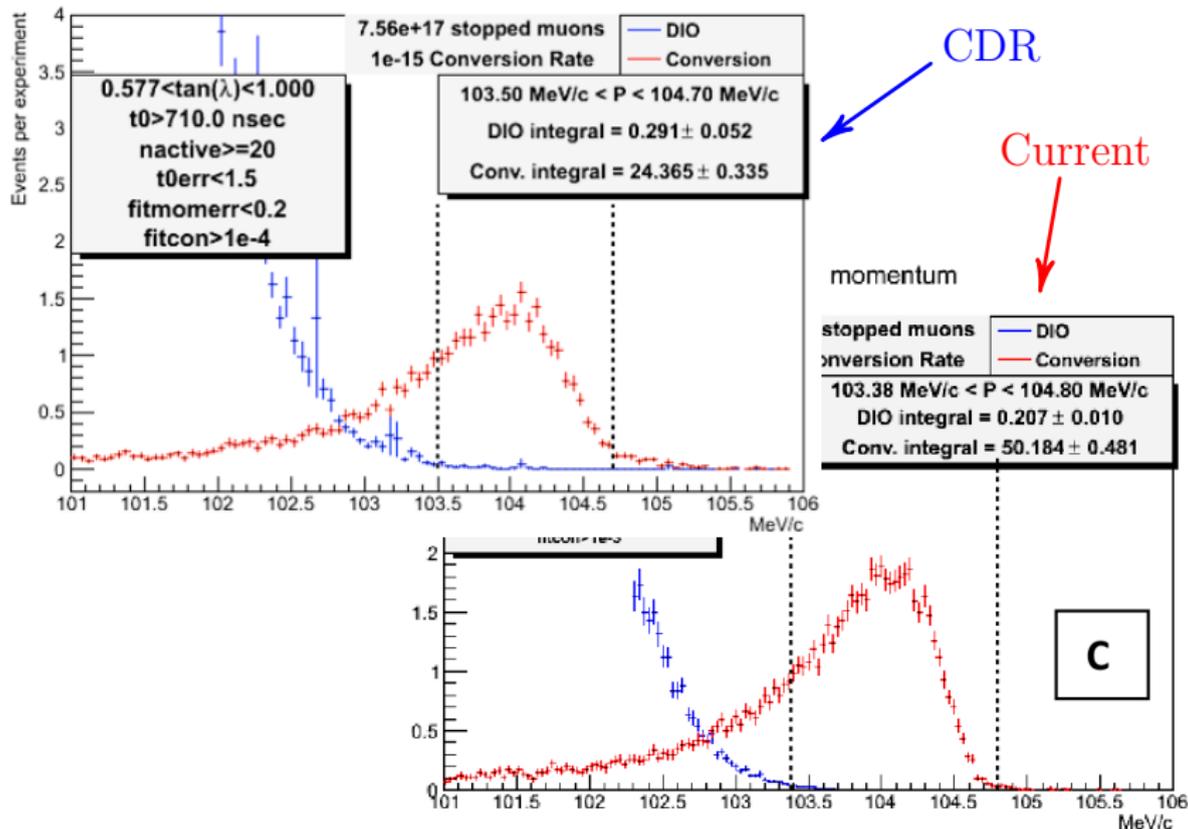
3 years of 1.2×10^{20} protons/year (8 kW beam power)

Background description	Expected events
Muon decay in orbit	0.22 ± 0.06
Antiproton induced	0.10 ± 0.05
Cosmic rays	0.05 ± 0.013
Radiative pion capture	0.03 ± 0.007
Muon decay in flight	0.01 ± 0.003
Pion decay in flight	0.003 ± 0.0015
Beam electrons	0.0006 ± 0.0003
Radiative muon capture	$< 2 \times 10^{-6}$
Total	0.41 ± 0.08

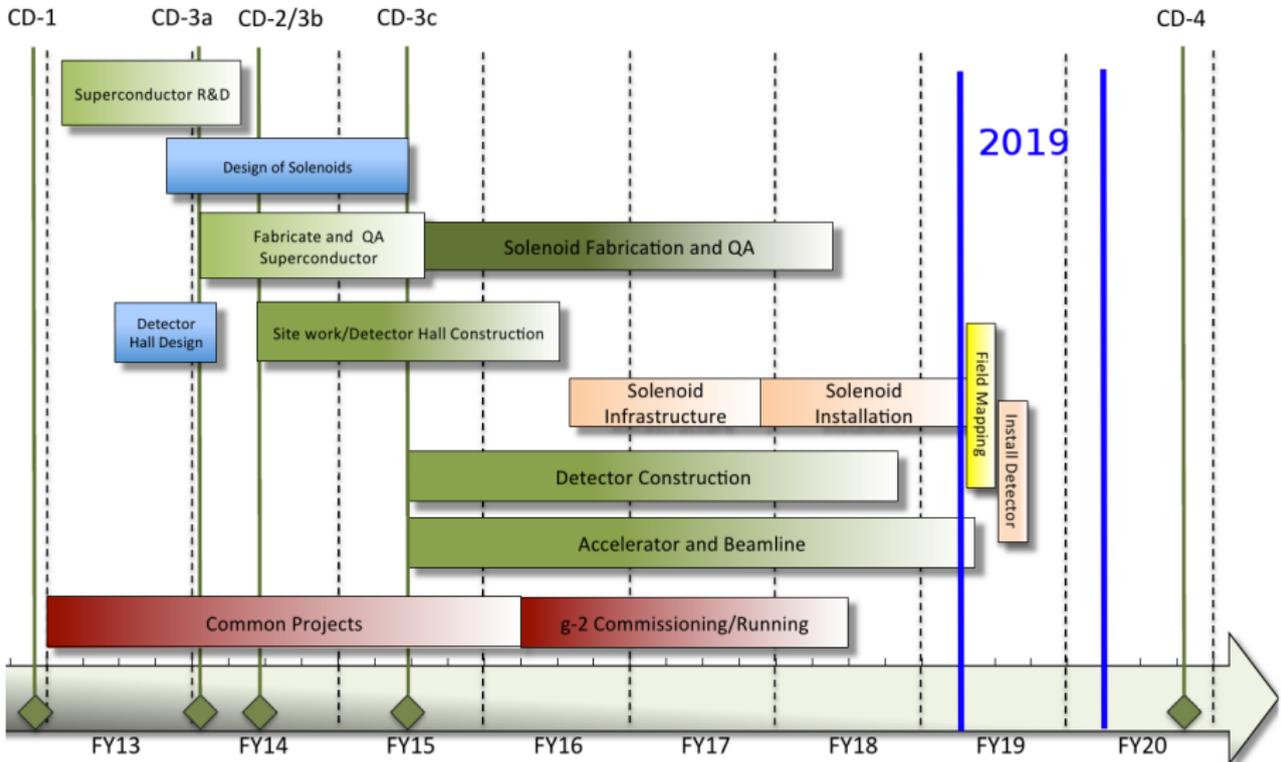
Preliminary code: $\approx 5 \times 10^{-17}$ single event sensitivity

Code improvements: expect $\approx 2 \times 10^{-17}$

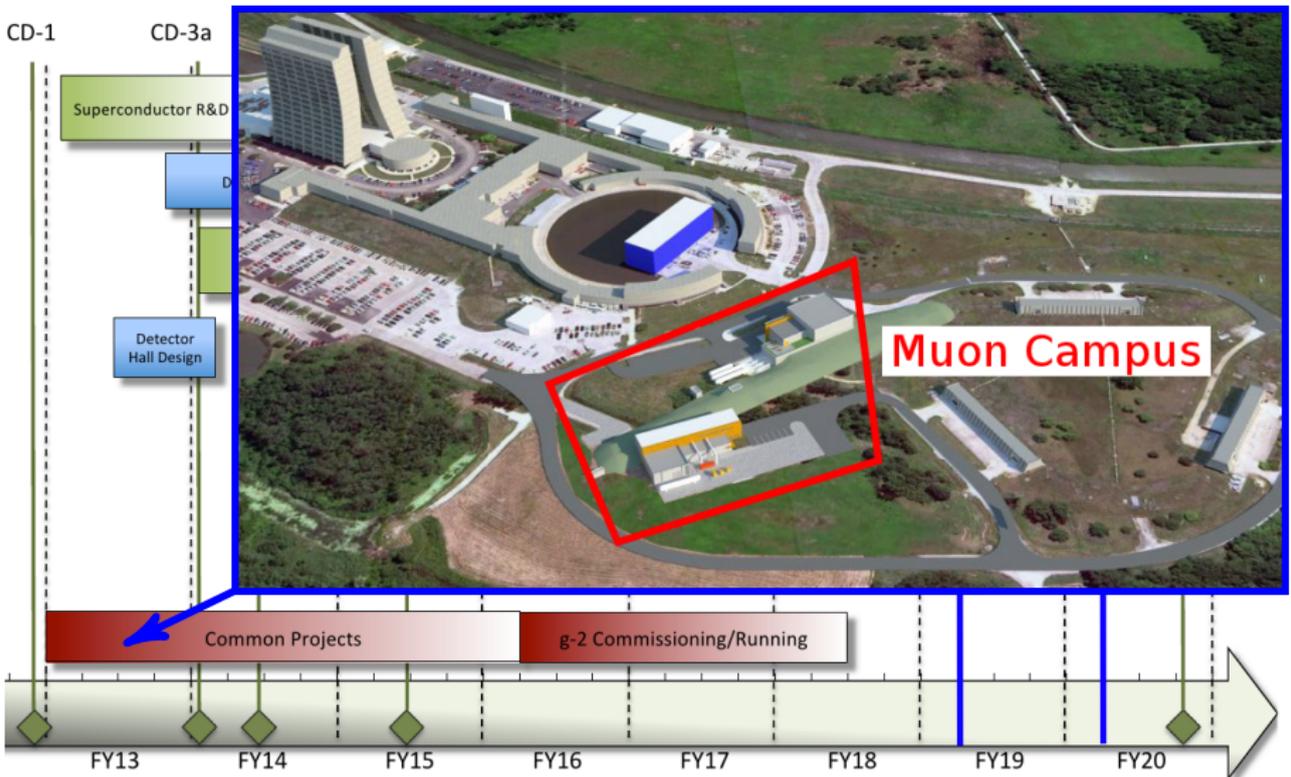
Recent tracking improvements



Schedule



Schedule



Conclusion

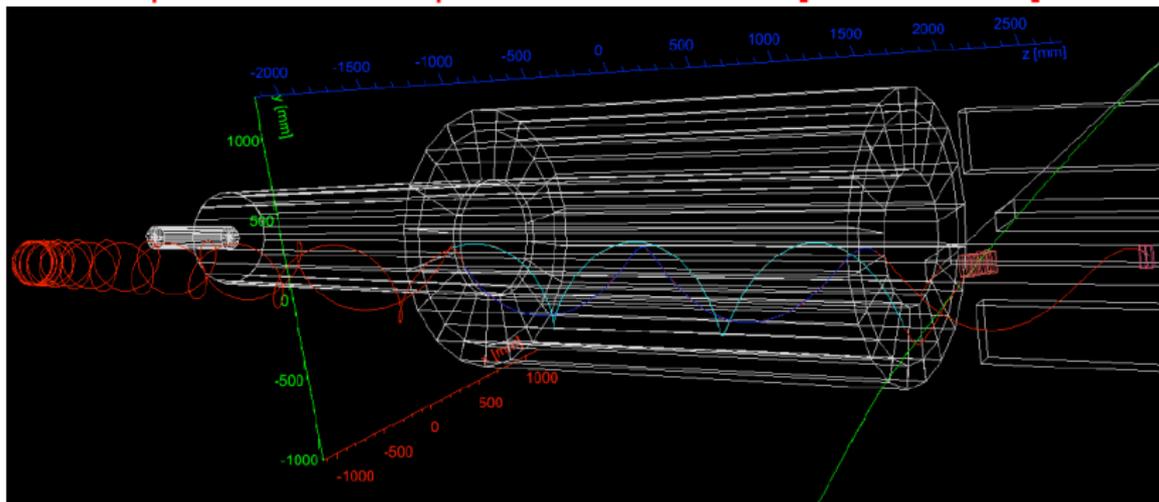
- Mu2e has an excellent **physics potential**
 - Aims for **4 orders of magnitude improvement**:
 $R_{\mu e} \approx 2 \times 10^{-17}$ **single event sensitivity**
 - New physics reach: Λ_{eff} up to **thousands of TeV**
- **Interesting whether New Physics is seen at the LHC or not**
 - Either help understand the New Physics
 - Or extend the LHC reach
- Conceptual design complete (DOE CD-1 in July 2012)
- Working towards technical design
- Data taking: about 2019

<http://mu2e.fnal.gov/public>

Extra slides

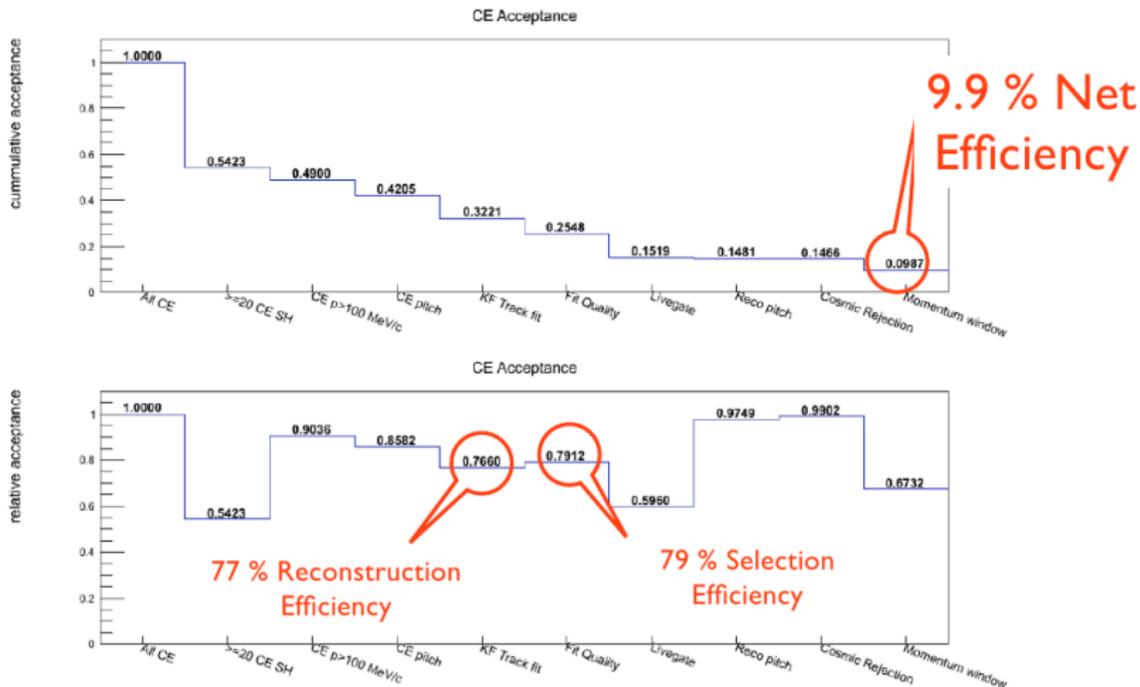
Tracker energy loss calibration

Double-pass of cosmic produced electrons [Dave Brown]

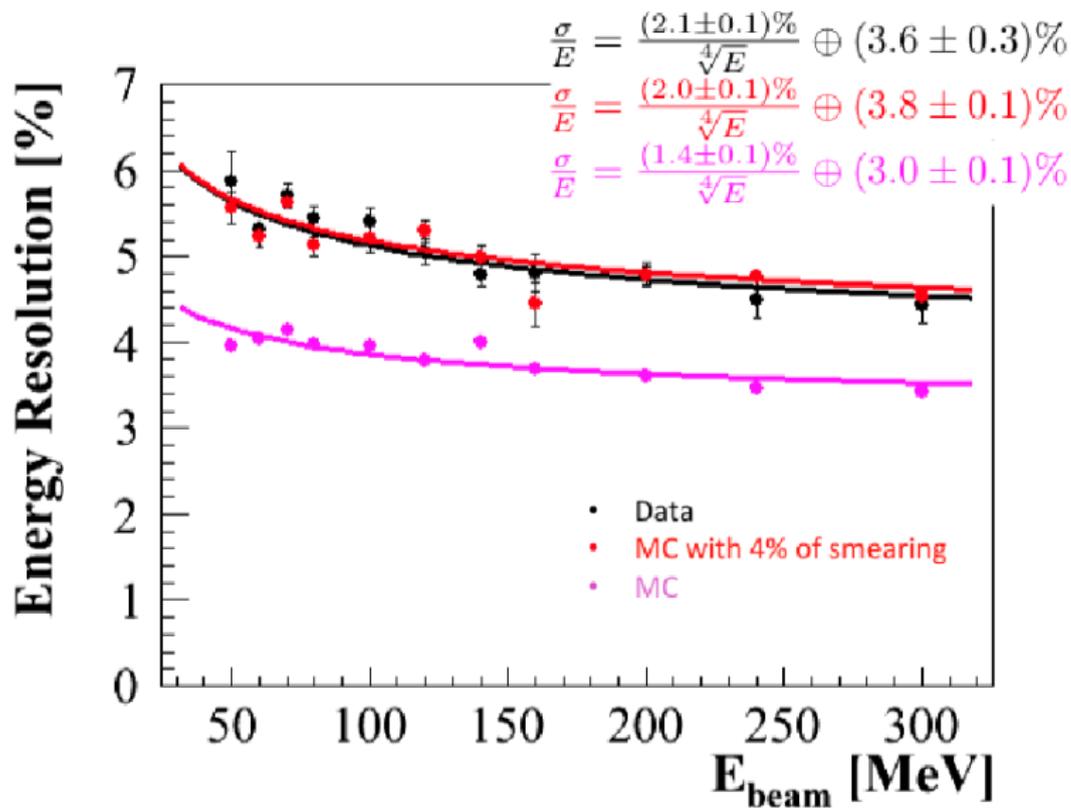


Signal reconstruction efficiency

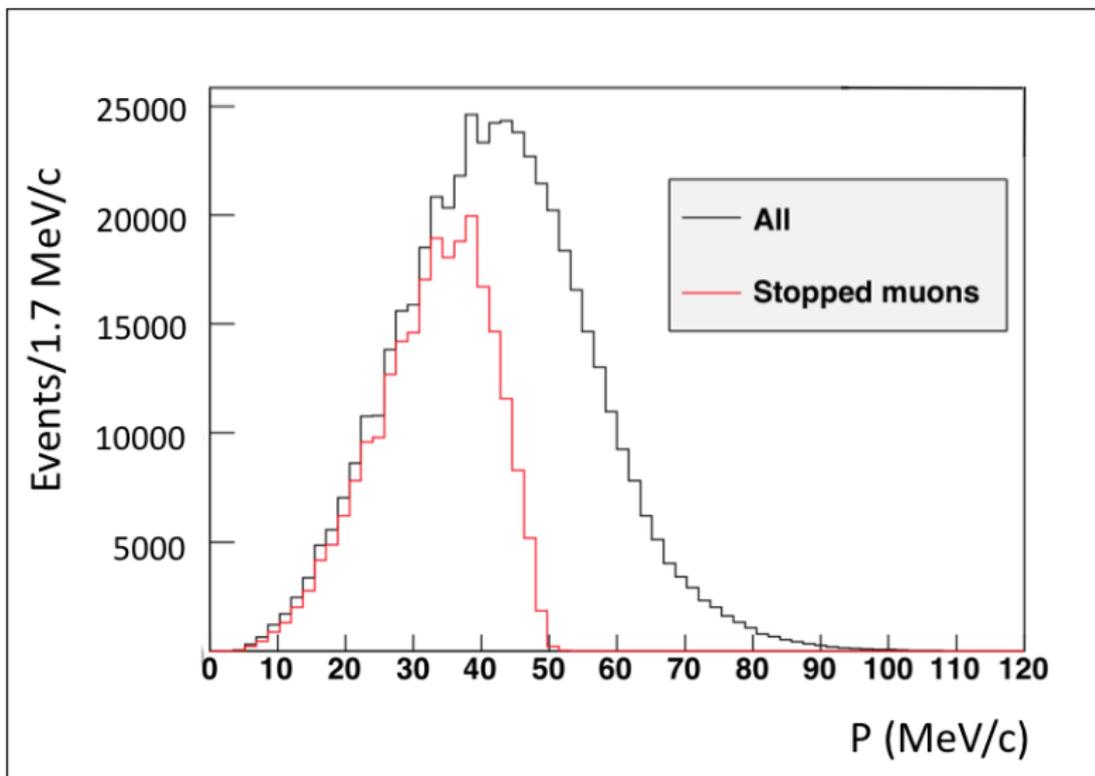
With a post-CDR version of code



LYSO crystal test beam

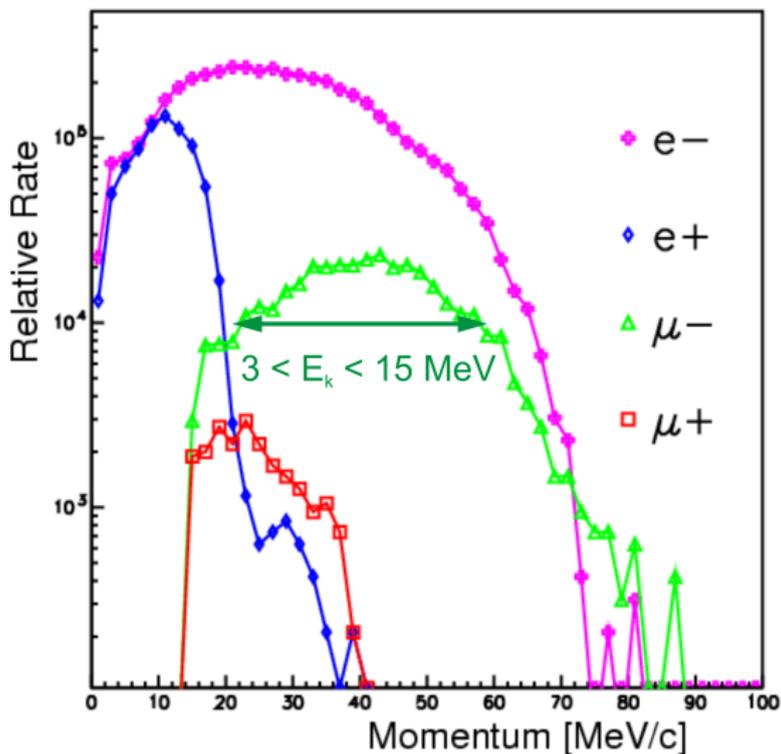


Muon momentum at the stopping target

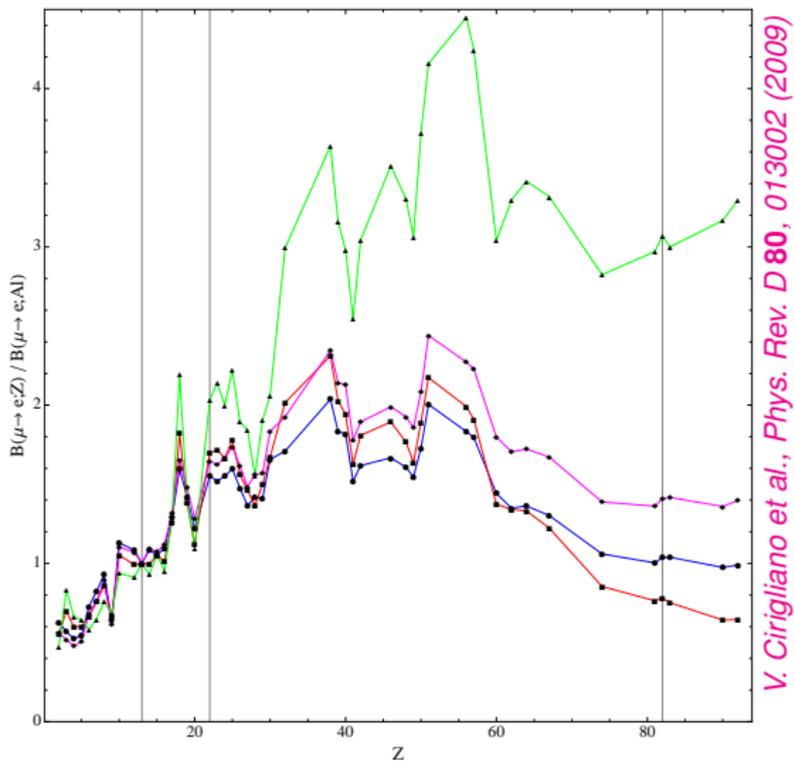


Muon beam particle composition

Pre-CDR beamline



Target Z dependence



V. Cirigliano et al., Phys. Rev. D **80**, 013002 (2009)